SIM PROJECT
PRELIMINARY INSTRUMENT SYSTEM
REQUIREMENTS REVIEW
(PISRR)

SIM Dynamics & Control Requirements

Flowdown Process

17-18 March, 1998
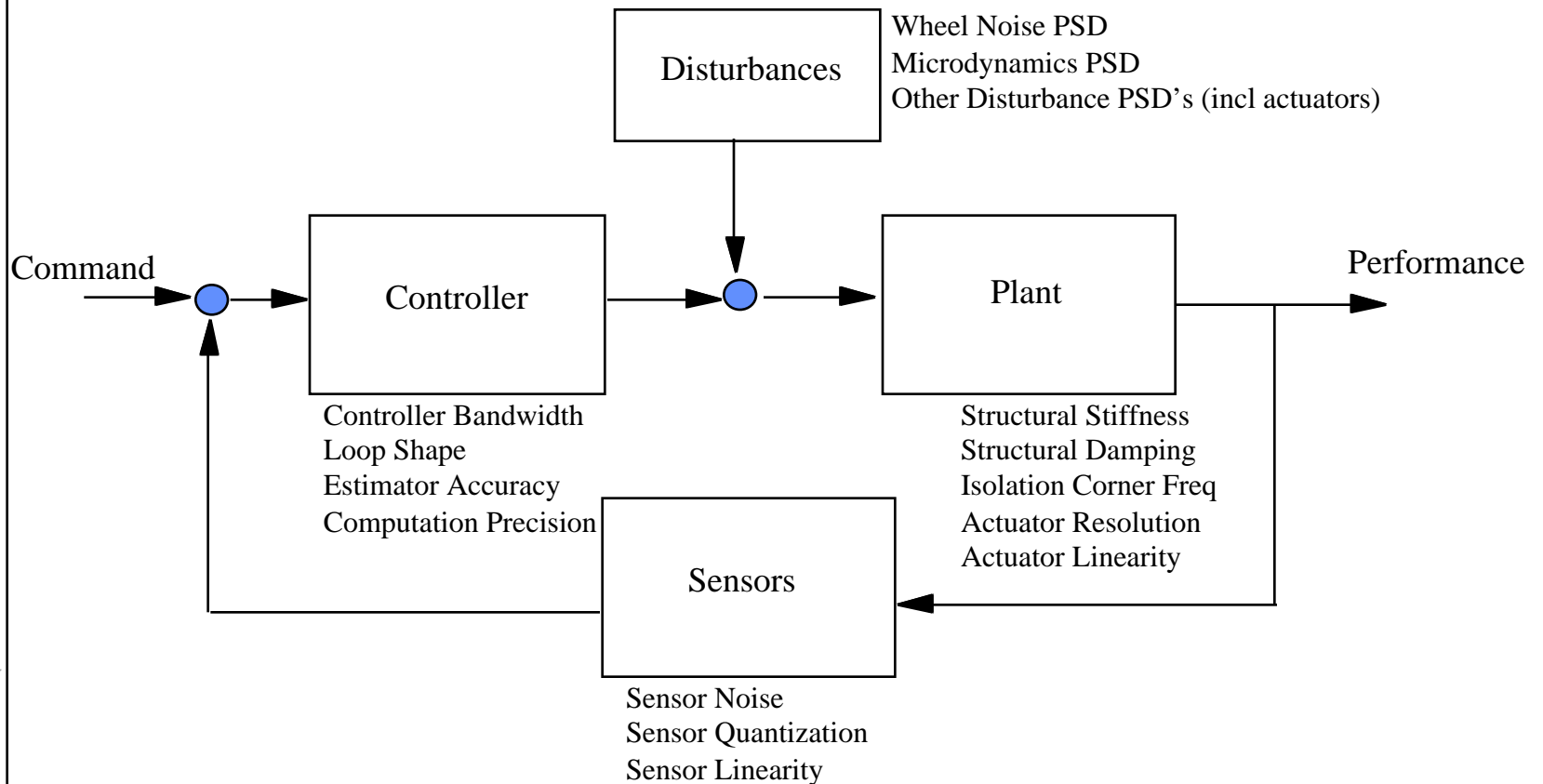
Robert A. Laskin

STB-3 Architect

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Space
Interferometry
Mission

CONTENTS

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Space Interferometry Mission

- **Motivation -- What's so special about Dynamics & Control Requirements Flowdown?**

- **Frequency Domain Mapping**
  - **Rule of thumb requirements**

- **Dynamics & Control Error Budgets**

- **Example -- 1 nm pathlength stabilization for nulling**
  - **Error Budget**
  - **Allocation of requirements across subsystems**
  - **Role of integrated modeling & testbeds**
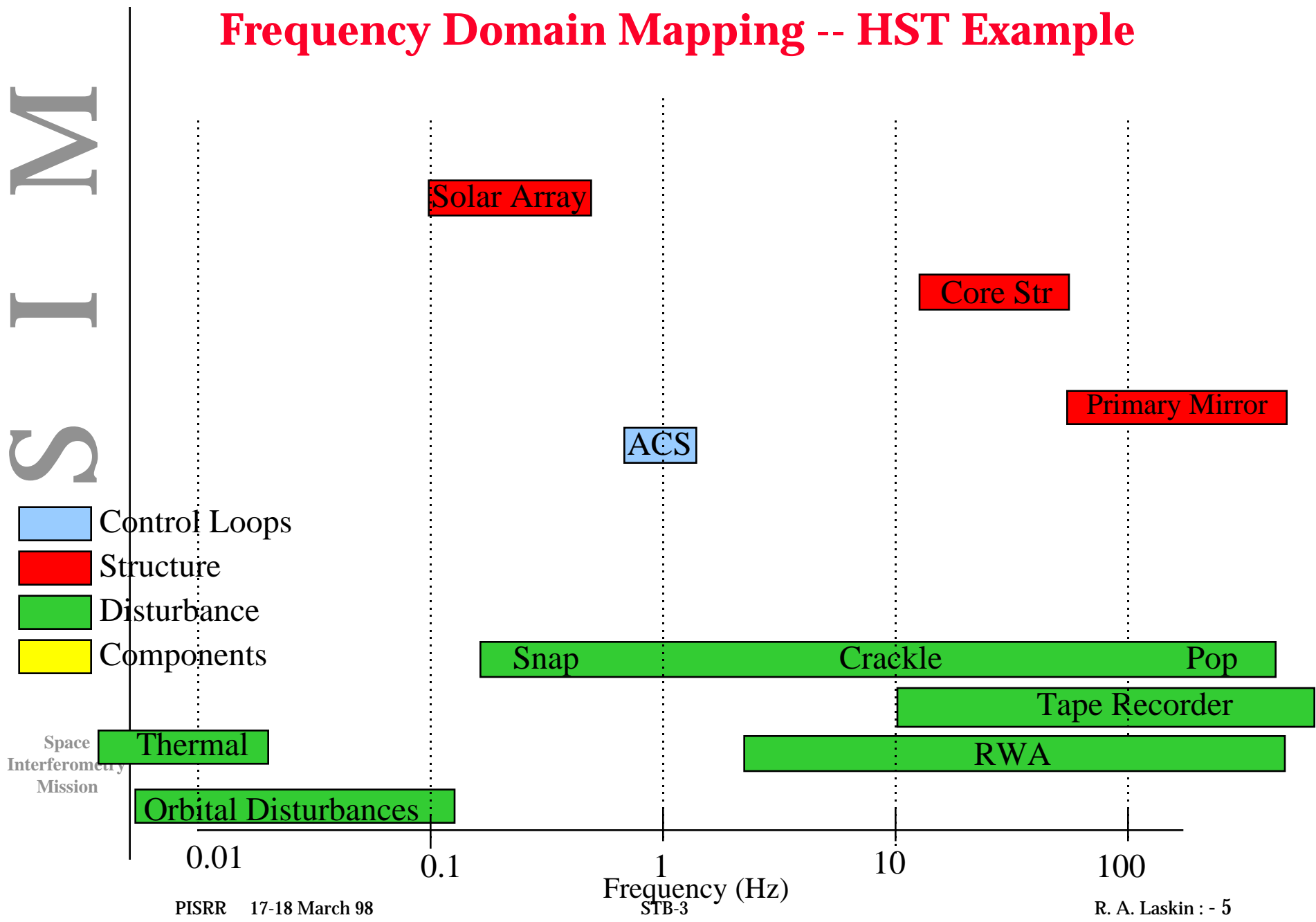
- **Summary/Conclusion**

Motivation

- **Dynamics & control requirements tend to crosscut multiple subsystems**
  - => **trades need to be made at the system level**

S I M (vertical, left margin)

Space Interferometry Mission (left margin)

Disturbances

Wheel Noise PSD
Microdynamics PSD
Other Disturbance PSD's (incl actuators)

Command

Controller

Controller Bandwidth
Loop Shape
Estimator Accuracy
Computation Precision

Plant

Performance

Structural Stiffness
Structural Damping
Isolation Corner Freq
Actuator Resolution
Actuator Linearity

Sensors

Sensor Noise
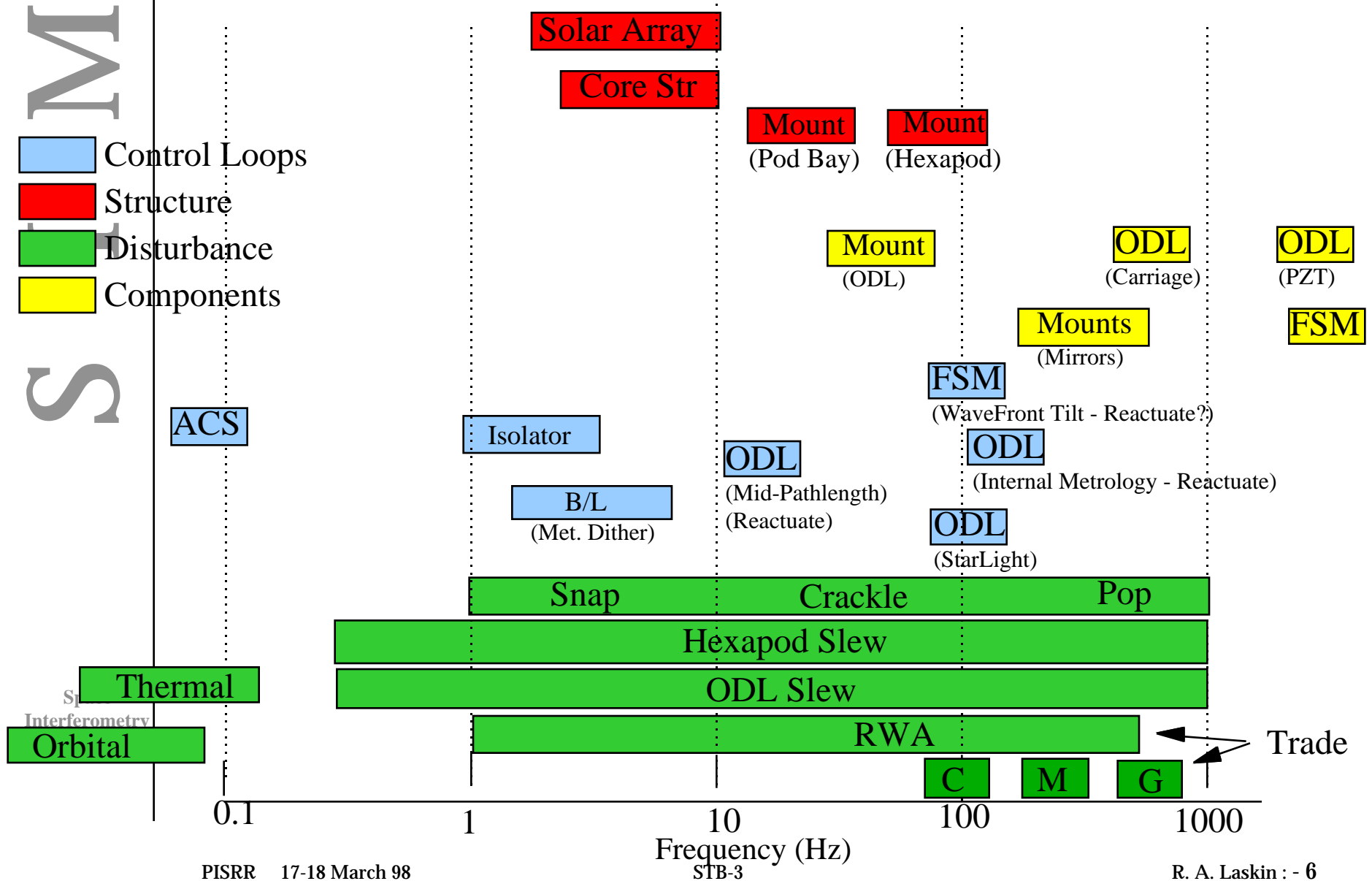Sensor Quantization
Sensor Linearity

Frequency Domain Mapping

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- Determine the critical temporal frequencies that govern major parts of the system
  - Disturbance frequencies
    - > space environment -- thermal radiation, solar pressure
    - > on-board machinery
    - > microdynamics -- snap, crackle, pop
  - Control system bandwidths
    - > ACS
    - > active optics
  - Structural modes
    - > appendage modes
    - > core structure modes
    - > optical bench mounting modes
    - > optical component mounting modes
- Try to enforce frequency separation if possible
- Bootstrap: disturbance freq => control BW => structural freq ....
- Can trade amplitude for frequency separation

Frequency Domain Mapping -- HST Example

Control Loops
Structure
Disturbance
Components

Solar Array

Core Str

Primary Mirror

ACS

Snap   Crackle   Pop

Tape Recorder

Thermal   RWA

Orbital Disturbances

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0.01   0.1   1   10   100

Frequency (Hz)

PISRR   17-18 March 98   STB-3   R. A. Laskin : - 5

Preliminary SIM Frequency Domain Mapping

SIM

Legend:
- Control Loops (blue)
- Structure (red)
- Disturbance (green)
- Components (yellow)

Structure:
- Solar Array
- Core Str
- Mount (Pod Bay)
- Mount (Hexapod)

Components:
- Mount (ODL)
- ODL (Carriage)
- ODL (PZT)
- Mounts (Mirrors)
- FSM

Control Loops:
- ACS
- Isolator
- FSM (WaveFront Tilt - Reactuate?)
- ODL (Mid-Pathlength) (Reactuate)
- ODL (Internal Metrology - Reactuate)
- B/L (Met. Dither)
- ODL (StarLight)

Disturbance:
- Snap | Crackle | Pop
- Hexapod Slew
- ODL Slew
- Thermal
- RWA
- Orbital
- C M G

Trade

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Frequency (Hz)

0.1   1   10   100   1000

Rule of Thumb Based Requirements Allocation

- ACS bandwidth < 0.1 Hz
  - disturbances are all low frequency
  - amplitudes are low
  - pointing requirement is modest
- Core structure fundamental frequency > 5 Hz (stiff as practical)
  - wide separation from ACS bandwidth
  - minimize thermal deformation
  - hold tight alignment tolerances
  - minimize vibration transmission
- Actuated body much stiffer than control loop
  - FSM   1000 Hz
  - ODL PZT mounted mirror   3 kHz
- Reactuate where structural interaction with support structure is likely
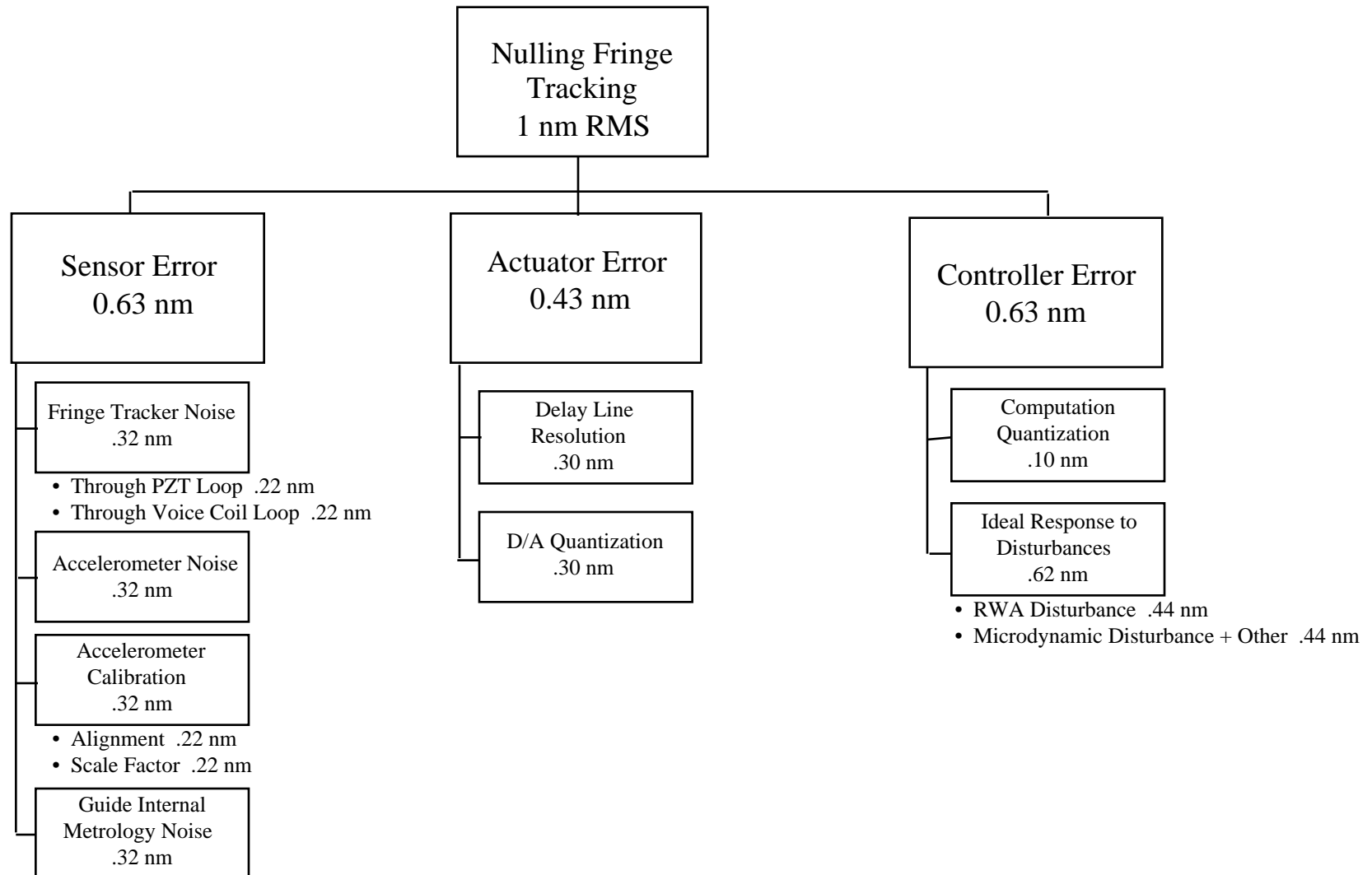 - ODL PZT
  - ODL Voice Coil
  - FSM?

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Error Budget Based Requirements Allocation

- Develop a dynamics & control error budget for each system mode
- Allocate errors to an a priori "level of equal pain" using engineering judgement
  - what is equal pain (cost, schedule, technical risk)
  - will top level requirement be met
- Reallocate errors in an iterative fashion
  - based upon models & analysis
    - > integrated models: controls, structure, optics
    - > start simple: optical sensitivity matrix, modal gain analysis, shock spectrum analysis, preliminary disturbance models, controller "filters"
    - > increase fidelity over time (e.g., incl. pod, hex, optics modes)
    - > put the requirements into the model
  - based upon testbed and bench testing
    - > STB-1 and STB-3
    - > component testing
  - based upon screams of pain (calibrate the whiners)
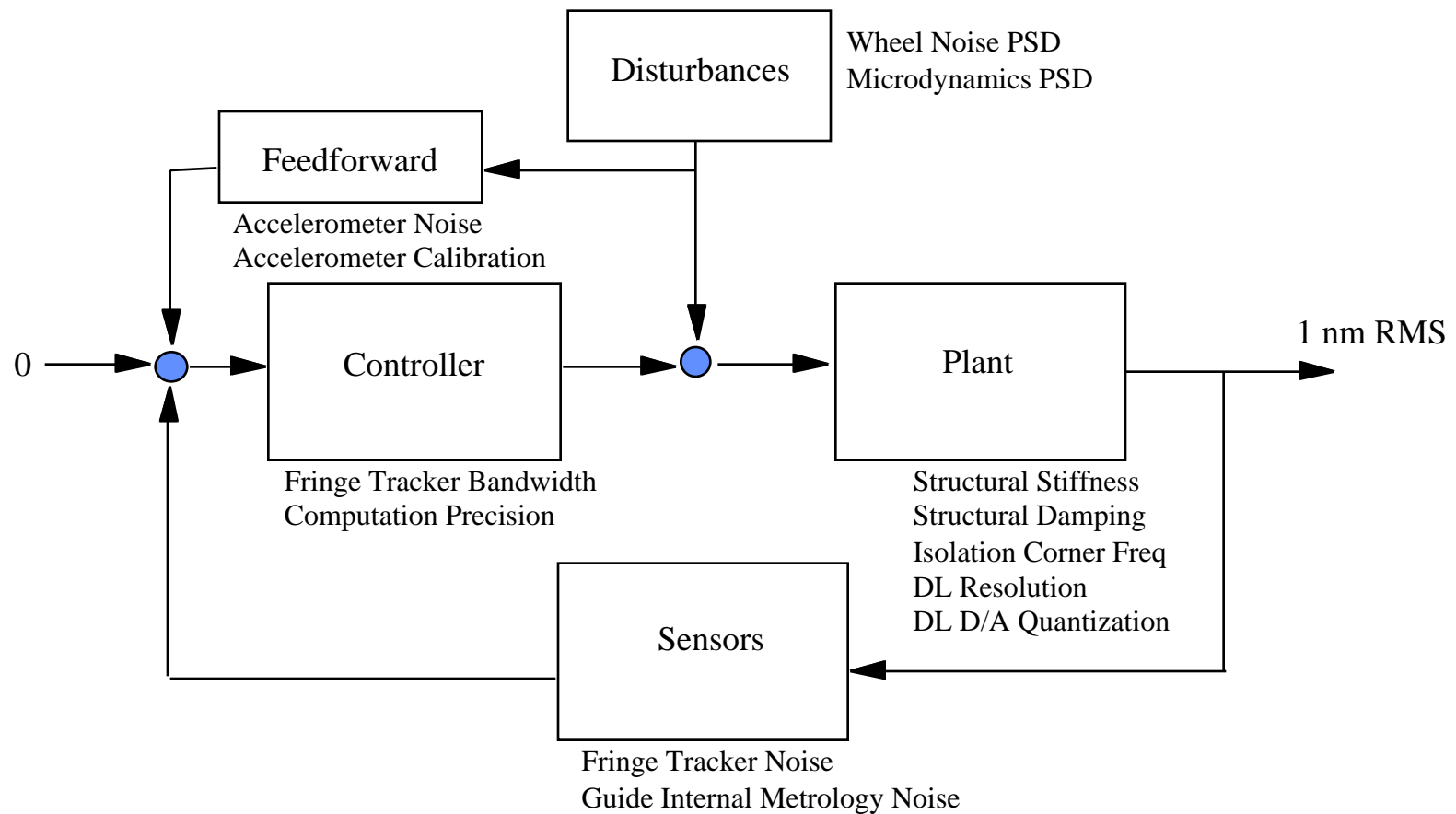
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SIM Dynamics & Control Error Budgets

- Nulling Fringe Tracking - 1nm
- Nulling Angle Tracking - TBD mas (TBD mas on sky)
- Guide Star Fringe Tracking - 10 nm
- Science Star Fringe Tracking - 10 nm
- Guide Star Angle Tracking - 30 mas (30 mas on sky, 330 mas on detector)
- Science Star Angle Tracking - 30 mas
- Guide Star Fringe Acquisition - 80 nm
- Science Star Fringe Placement (for Acquisition) - 25 um
- Guide Star Angle Placement (for Acquisition) - 1 arcsec
- Science Star Angle Placement (for Acquisition) - 3 arcsec
- Fringe and Angle Tracking for Imaging - TBD nm, TBD mas
- Guide Fringe Lock During Slews - TBD nm jitter
- Guide Angle Lock During Slews - TBD mas jitter
- Metrology Lock During Slews - TBD nm jitter
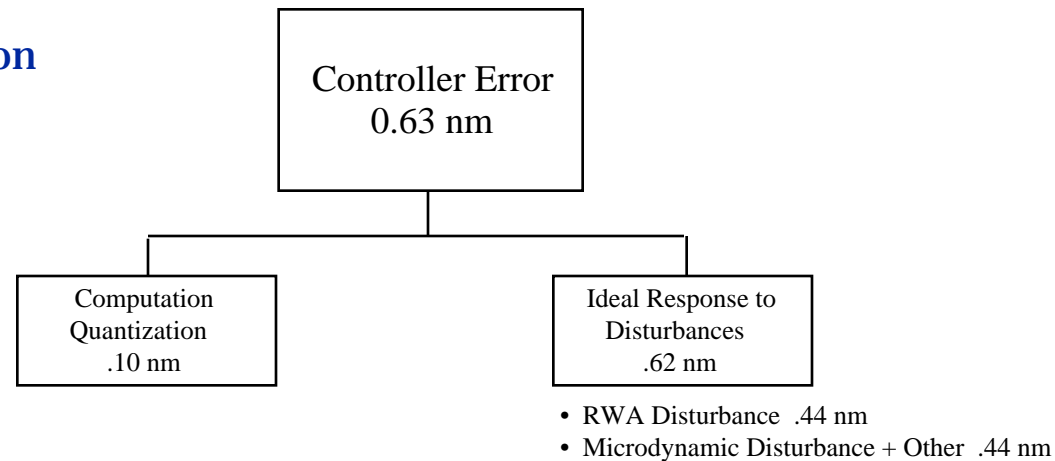- Settling Time Post Slews - TBD seconds

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Example -- 1 nm Pathlength Stabilization

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```
                    Nulling Fringe
                       Tracking
                      1 nm RMS

    Sensor Error         Actuator Error        Controller Error
     0.63 nm                0.43 nm               0.63 nm
```

Sensor Error branch:

- Fringe Tracker Noise .32 nm
  - • Through PZT Loop .22 nm
  - • Through Voice Coil Loop .22 nm
- Accelerometer Noise .32 nm
- Accelerometer Calibration .32 nm
  - • Alignment .22 nm
  - • Scale Factor .22 nm
- Guide Internal Metrology Noise .32 nm

Actuator Error branch:

- Delay Line Resolution .30 nm
- D/A Quantization .30 nm

Controller Error branch:

- Computation Quantization .10 nm
- Ideal Response to Disturbances .62 nm
  - • RWA Disturbance .44 nm
  - • Microdynamic Disturbance + Other .44 nm

Example -- 1 nm Pathlength Stabilization

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Disturbances

Wheel Noise PSD
Microdynamics PSD

Feedforward

Accelerometer Noise
Accelerometer Calibration

0

Controller

Fringe Tracker Bandwidth
Computation Precision

Plant

1 nm RMS

Structural Stiffness
Structural Damping
Isolation Corner Freq
DL Resolution
DL D/A Quantization

Sensors

Fringe Tracker Noise
Guide Internal Metrology Noise

Controller Errors

- **Error Allocation**

```
                    ┌─────────────────────┐
                    │   Controller Error   │
                    │      0.63 nm         │
                    └─────────────────────┘
                              │
               ┌──────────────┴──────────────┐
     ┌──────────────────┐         ┌──────────────────┐
     │   Computation    │         │ Ideal Response to │
     │  Quantization    │         │  Disturbances     │
     │     .10 nm       │         │     .62 nm        │
     └──────────────────┘         └──────────────────┘
```

- RWA Disturbance .44 nm
- Microdynamic Disturbance + Other .44 nm

- **Derived Requirements**

Computational Precision shall be less than .05 nm
Reaction Wheel Emitted Vibration (measured blocked) shall be less than Jim Melody Model
Isolator Corner Frequency shall be less than 2 Hz
Hardback 1st Modal Frequency shall be greater than 5 Hz
Hardback Modal Damping Ratio shall be greater than .1%
Collector Pod 1st Modal Frequency shall be greater than 25 Hz
Collector Pod Modal Damping Ratio shall be greater than .1%
Fringe Tracking Closed Loop BW (incl accels) shall be greater than 100 Hz
Persistent Microdynamics Background Vibration (typical point on structure) shall be less than 10 ug/rt(N)*
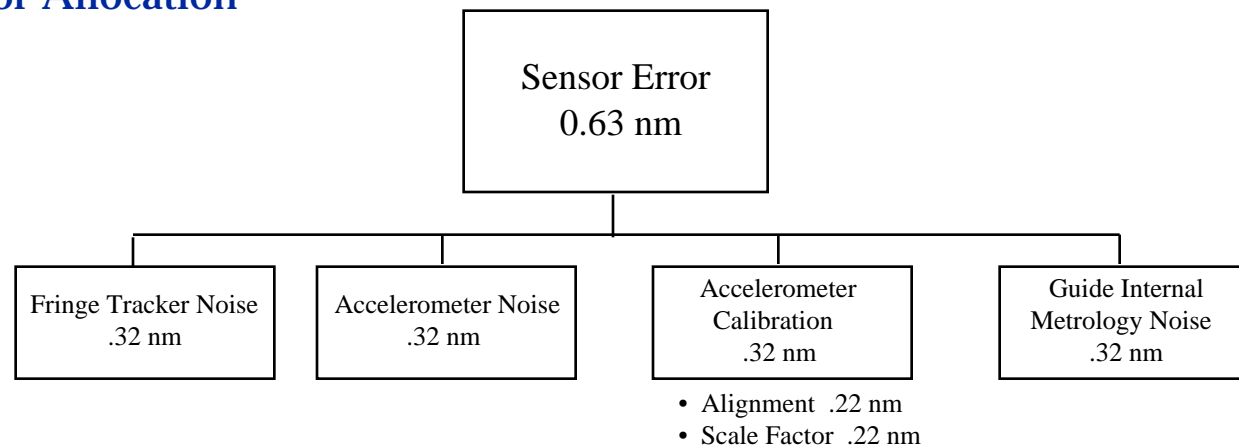Transient Microdynamics Disturbance Response (typical point on structure) shall be less than 1 cm/s or 50 nm
Transient Microdynamics Disturbance Response (typical point on structure) shall occur less than once per 10 minutes

* N = number of bounces in interferometer beam train
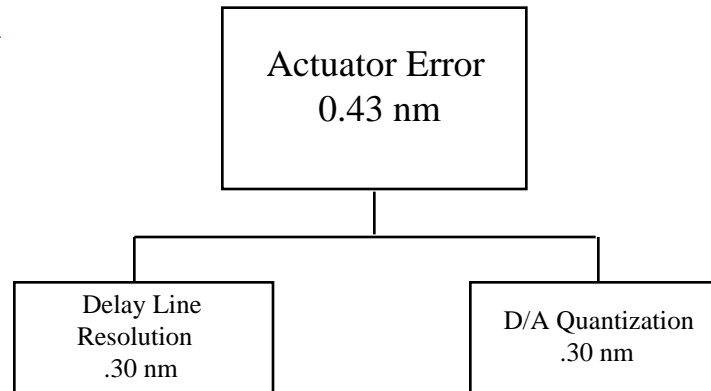
Sensor Errors

- **Error Allocation**

```
                    ┌─────────────────────┐
                    │    Sensor Error      │
                    │     0.63 nm          │
                    └─────────────────────┘
```

Fringe Tracker Noise .32 nm	Accelerometer Noise .32 nm	Accelerometer Calibration .32 nm	Guide Internal Metrology Noise .32 nm

- Alignment .22 nm
- Scale Factor .22 nm

- **Derived Requirements**

Fringe Tracker Noise within PZT Loop BW shall be less than .09 nm
Fringe Tracker Noise beyond PZT Loop BW shall be less than .09 nm (post-filtering)
Fringe Tracker Noise within VC Loop BW shall be less than .09 nm
Fringe Tracker Noise beyond VC Loop BW shall be less than .09 nm (post-filtering)
Accelerometer Noise within PZT Loop BW shall be less than .09 nm
Accelerometer Noise beyond PZT Loop BW shall be less than .09 nm (post-filtering)
Accelerometer Noise within VC Loop BW shall be less than .09 nm
Accelerometer Noise beyond VC Loop BW shall be less than .09 nm (post-filtering)
Accelerometer Calibrated Alignment to sensed axes shall be less than 260 urad (1 um amp, sin)
Accelerometer Scale Factor Calibration shall be less than .026% (1 um amplitude motion)
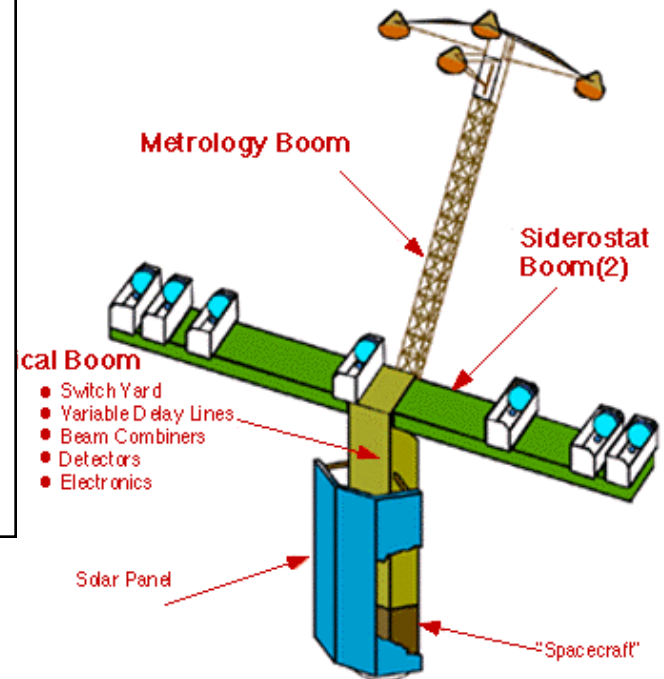Internal Metrology Sensor Noise shall be less than TBD

Actuator Errors

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- **Error Allocation**

```
          ┌─────────────────┐
          │  Actuator Error  │
          │     0.43 nm      │
          └────────┬─────────┘
            ┌───────┴───────┐
  ┌─────────────────┐   ┌─────────────────┐
  │   Delay Line    │   │ D/A Quantization │
  │   Resolution    │   │     .30 nm       │
  │     .30 nm      │   │                  │
  └─────────────────┘   └─────────────────┘
```

- **Derived Requirements**

PZT Mechanical Resolution shall be less than .15 nm
A/D Quantization Cmd to PZT shall be less than .15 nm

# SIM Classic 3 Baseline Integrated Model

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Metrology Boom

Siderostat
Boom(2)

cal Boom
- Switch Yard
- Variable Delay Lines
- Beam Combiners
- Detectors
- Electronics

Solar Panel

"Spacecraft"

Disturbance Analysis

- Hubble Space Telescope Harmonic Disturbance RWA Model
  - Model Force/Torque Induced Vibration as Blocked Force
  - Assume Spin Motor Disturbance (Ripple and Cogging) Small
  - Stochastic Broadband Model
  - Discrete-Frequency RWA Model
    - > Sweep over wheel speeds (0 to 3000 RPM)

F(radial)
T(wobble)
T(ripple+cogging)
F(axial)

- OPD vs. RPM
  - Each Point Represents Standard Deviation of the Discrete Frequency PSD of OPD Resulting From the Disturbance of a Single RWA at a Given Speed
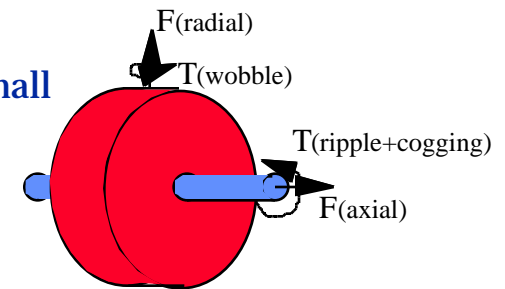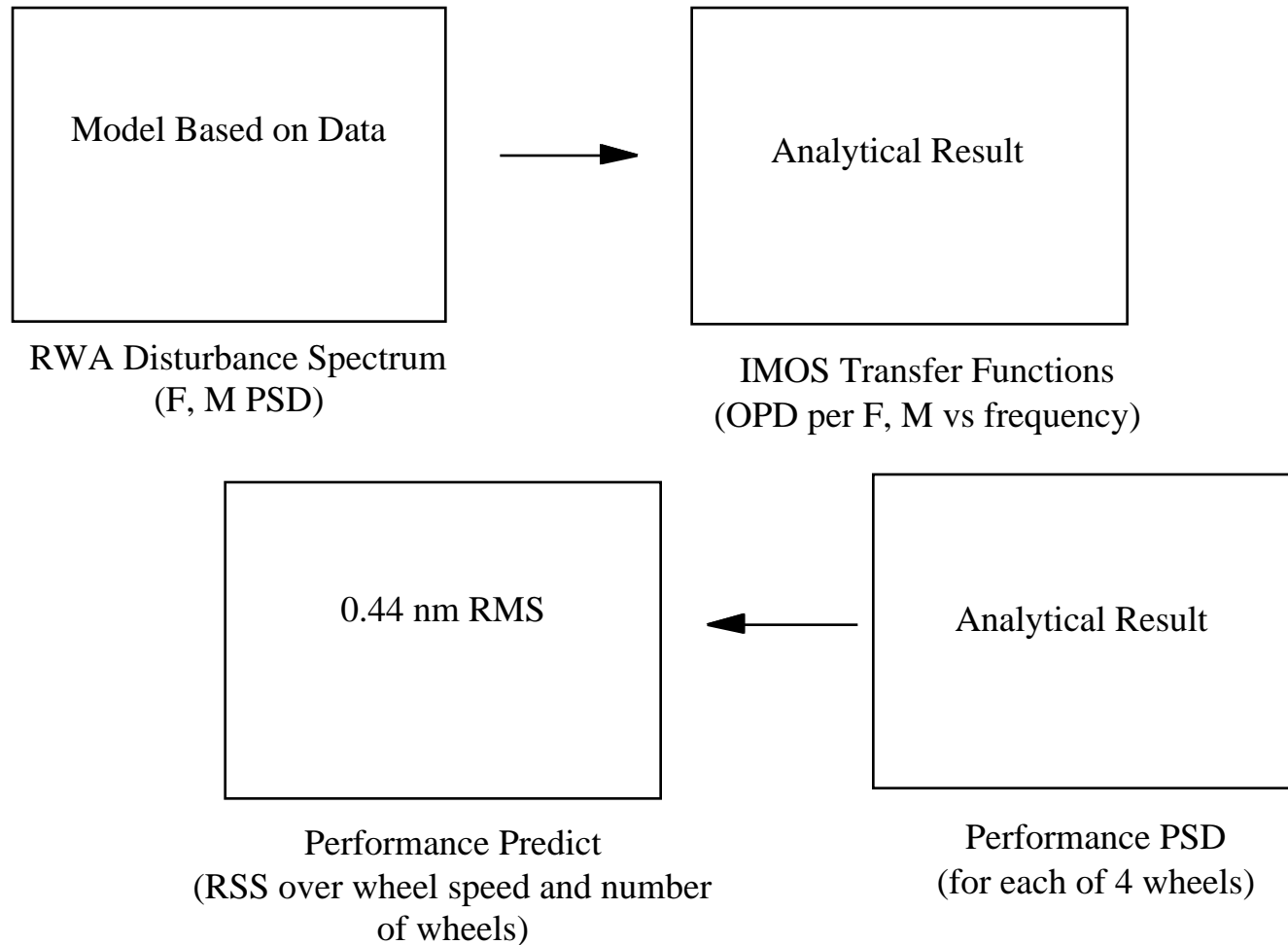
$$IV(t) = \sum_{i=1}^{n} C_i f_{RWA}^2 \sin\left(2\pi h_i f_{RWA} t + \alpha_i\right)$$

$$\sigma_{opd}^2(f_{RWA}) = \int \left| G(j\omega)_{\frac{OPD}{RWA}} \right|^2 \Phi(\omega, f_{RWA}) d\omega$$

- RWA High Frequency Signature Is Unique
  - Bearing Geometry, Bearing Race, Cage Speed, Operating Temp, Lubrication, Life
  - Model Flexibility Rolloffs With Parameterized Filters
  - Housing Flexibility, Bearing Impedance (100 Hz)
  - Statistically Bound Problem Using Many RWA Models

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Performance Prediction with IMOS Model

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```
┌────────────────────┐                    ┌────────────────────┐
│                    │                    │                    │
│ Model Based on Data│ ────────────────▶  │  Analytical Result │
│                    │                    │                    │
└────────────────────┘                    └────────────────────┘
```

RWA Disturbance Spectrum
(F, M PSD)

IMOS Transfer Functions
(OPD per F, M vs frequency)

```
┌────────────────────┐                    ┌────────────────────┐
│                    │                    │                    │
│   0.44 nm RMS      │ ◀────────────────  │  Analytical Result │
│                    │                    │                    │
└────────────────────┘                    └────────────────────┘
```

Performance Predict
(RSS over wheel speed and number
of wheels)

Performance PSD
(for each of 4 wheels)

Sensitivity Chart

Testbed Reality Chart

Hardware Testing Makes It Real

- The testbeds inform the process of dynamics/control requirements allocation in two major ways:
  - Supply real numbers to put in the error budget boxes
  - Validate the allocation process
    - same methodology is applied to the testbeds
    - error propagation assumptions can be checked
- STB-1 and STB-3 -- where the rubber meets the road for dynamics and control requirements flowdown

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Summary

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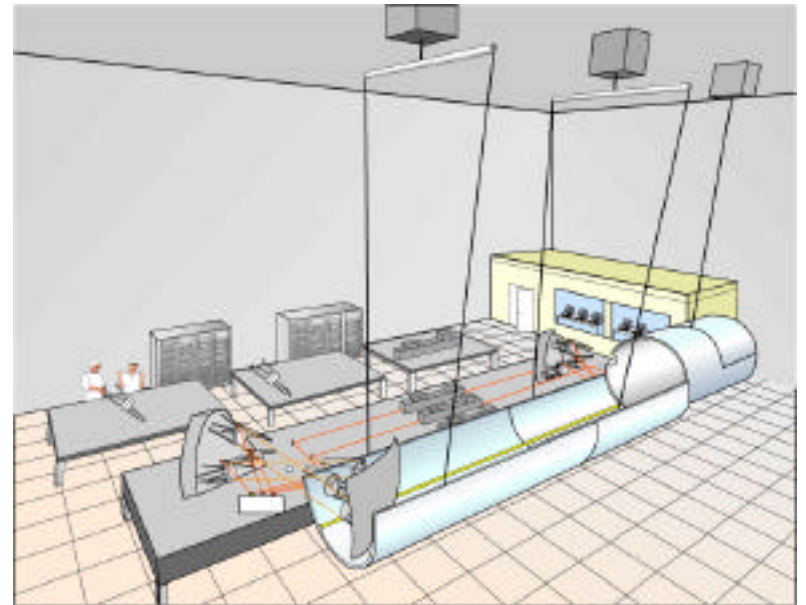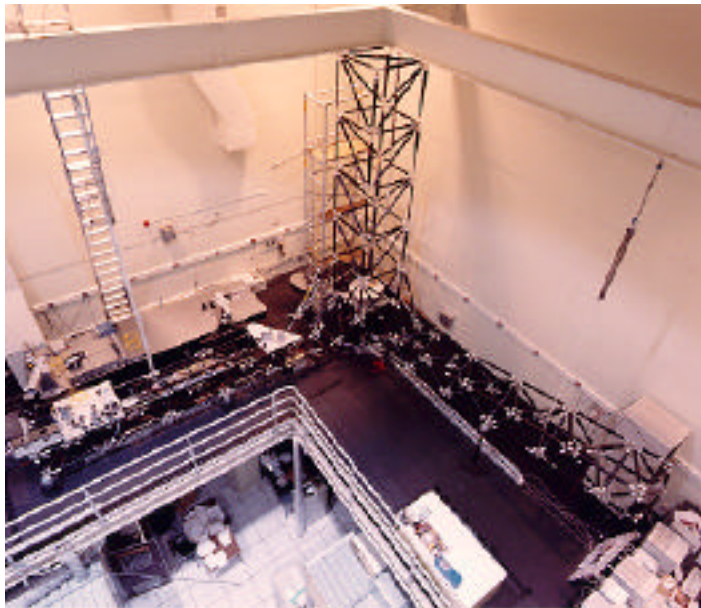
- Defined a process for flowdown of SIM dynamics/control requirements

- Need to work the process for the new architecture
  => Begin building a low complexity integrated model ASAP

- STB-1 and STB-3 will be key system testbeds for validating dynamics/control requirements flowdown/flowup

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